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The Coordinated Control of FACTS and HVDC Using H-infinity Robust Method to Stabilize the Inter-regional Oscillations in Power Systems

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ABSTRACT

This paper presents a new resistant control method for synchronized connection of FACTS & HVDC aiming to get the stability of small signal of the power system. The efficiency of the proposed controller on the stability of the entire tested system has been proved and also guarantees the stability against uncertainty and turmoil. Applying this method can also reduce the difficulties of oscillations between adjacent areas to generator without strengthening transmission lines or costly constraints on system performance. The simulation results on a system of 68 buses, 16 generators and 5 areas show that the mentioned controller with embedded HVDC and SVC has significant performance despite changes in parameters.

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1. INTRODUCTION

Nowadays for maintaining economic power with higher reliability, power systems of different geographical areas are increasingly connected to each other by long lines. Statistics show that one of the main causes of system blackouts is low frequency oscillations between the areas adjacent to the generator in these systems. HVDC systems possess the capacity of fast control of power, the ability which can be used to improve the stability of power systems. To improve the stability and reduce oscillations of the set, additional controllers along with FACTS devices are required. While it has been more than a few decades that the mentioned method is used to improve the dynamic stability, different methods for designing these controllers have been introduced [1]. Among the primary methods, the linearization law of feedback can be used to convert nonlinear third phase model of generator to linear closed loop system [2]. GROUDE used Kalman filter method to do this. VOVOS also applied estimator design method along with Kalman filter. The drawback of these two methods they don’t possess the property of disturbance rejection and sensitivity to the parameters changing [3]. The next proposed method was the use of optimal control theory. The main problem of this method is its selection strategy of weight matrices of Q and R in standard function [4]. Other methods such as artificial intelligence [5], pole replacement [3], neural networks [6], the phase controller [8] and [7], genetic algorithm [10] and [9] have also been used. In the process of designing these methods, since uncertainty does not model correctly and structurally, the controller may under certain conditions provide unacceptable activities. On the other hand, it is usually difficult to find structural uncertainty in the power system for connecting the before error condition to after error condition. In order to solve the mentioned

problems, our proposed method that is the resistant control method by using function weights and uncertainties removes sensitivity to parameter changes and repels disturbances. In addition, by installing the required equipment for FACTS and HVDC in different areas of generator, the maximum level of stability as well as the maximum level of protection against power system disturbances will be achieved. In this paper, at first the general applied model of FACTS and HVDC along with the relationships will be introduced. Then, the theory and design of resistant controller will be discussed. Finally, analyzing the specific values of the system and also applied simulations on Mira modes of oscillation between different generator areas of the studied system will be dealt with.

2. MODELING

2.1. The Modeling of the Transmission Lines of HVDC and HVAC

HVDC transmission systems are particularly important nowadays and because of their special features, they are getting more attention. These systems in transmitting the power for long distances, long underground transmission lines, and connecting two power networks without disturbances have wide applications. One problem of these lines is high cost of converting AC to DC equipment and vice versa, though it is economically feasible for the HVDC transmission [11]. For example, in the transmission distance of over 600 km and underground cable transmission (more than 50 km) to connect the islands to the network there are conditions that justify the HVDC system economically. While HVDC lines require only 2 conductors that is one with a positive voltage and another with a negative voltage in relation to the ground, at least three conductors are needed for HVAC transmission lines. Thus, the amount of sequence and transition current in AC and DC transmission lines can be determined as follows [12, 21]:

$$P_{AC} = \sqrt{3} V I_{AC} \cos\varphi \tag{1}$$

$$I_{AC} = P_{AC} / \sqrt{3} V \cos\varphi \tag{2}$$

$$P_{DC} = 2 V I_{DC} \tag{3}$$

$$I_{DC} = P_{DC} / 2V \tag{4}$$

The rreliability of HVDC lines is more than HVAC lines, because despite a fault in one of the two conductive lines the transmission power can still be passed through the other conductor without any problem. Given that the HVDC line includes two conductors, in comparison with the similar HVAC it requires less space and therefore requires smaller bases, and as a result is less costly to install than HVAC.The maximum voltage range of each AC system is:

$$\frac{\sqrt{2}}{\sqrt{3}} V_{ll} = 0.8 V_{ll} \tag{5}$$

And the maximum system voltage of DC is:

$$\frac{1}{2} V_{ll} = 0.5 V_{ll} \tag{6}$$

There is no problem of maintaining synchronization between two systems of AC that are connected by an HVDC line. In addition, the same frequency of two networks of AC that are connected by an HVDC line is not needed. Moreover, in case of short circuit occurrence in one of the two AC networks that are connected by a DC line, the short-circuit current is not transferred to another network, because short-circuit current is generally a reactive current and in the DC system reactive current is not transferred and $\cos\varphi$ equals 1.The transmission power from a DC line can be easily controlled by its thyristor rectifier and be maintained in a certain amount. Since reactive current doesn't exist in DC lines, HVDC line losses are fewer than the lines of HVAC. In HVAC lines, the transmission power is equal $P = \frac{V_1 V_2 sin\, S}{X}$ and due to transient modes in these lines, the angle of S in normal condition must be less than 30 degrees. So, AC lines face line length and transmission power limitations and series capacitors are used to address the problem. But, in HVDC lines there will be no stability constraints.Although due to the high cost of AC to DC and DC to AC converters the cost of HVDC lines is very high, for long distance lines from 600 to 900 km and powers more than 100 MW, DC lines will be less costly than AC lines . This issue is particularly more significant for the

DC cables that for distances of 50 to 100 km would be more economical. At the time of two AC networks connection, HVDC asynchronous system will be used. In HVDC system, the capacity of load portion will increase in a way that the level and the path of power transmission can be specifically and broadly controlled and in case of DC sources on the way it can be supplied. In addition, there will be no need for common frequency in the network and the earth can be used as the return line [19].

2.2. Modeling of Static Var Compensator (SVC)

SVC is connected to the network in a parallel way and as Figure (1) shows the features of VI voltage of SVC current may appear in inductive or capacitive reactive modes. In the larger capacitor current, SVC transforms to a capacitor and its reactive power changes as a function of voltage.

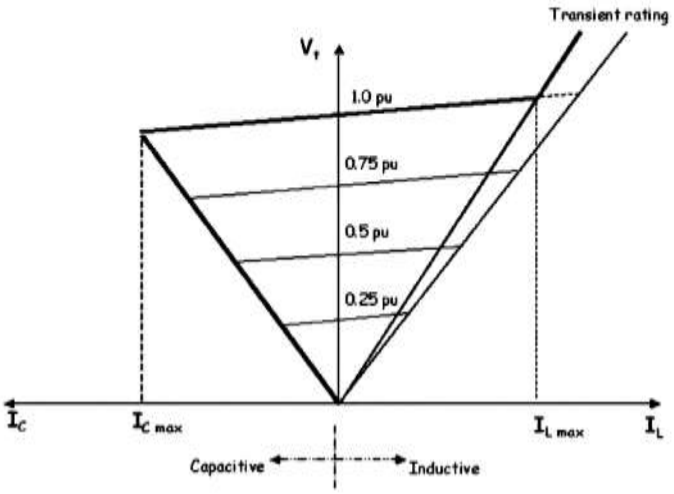

Figure 1. Voltage - the SVC current characteristics (V-I)

With proper coordination of capacitor switching and reactor control, the reactive output can be considered as shifting continuously between capacitive and inductive values [13, 20, 21].

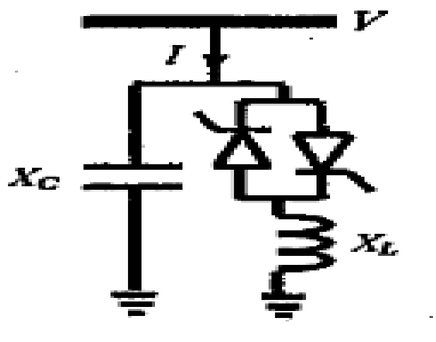

Figure 2. The structure of SVC

Now, if we model SVC as shown in Figure (2) the formulation would be as follows [14]:

$$X_{Leq} = X_L \frac{\pi}{2(\pi - \alpha) + \sin(2\alpha)} \tag{7}$$

Where there is the firing angle of thyristor, the impact of the SVC reactance can be achieved by the parallel combination:

$$X_{eq} = \frac{X_c X_L}{\frac{X_c}{\pi}(2(\pi - \alpha) + \sin(2\alpha)) - X_L} \tag{8}$$

SVC Susceptance is presented in Equation 9 while its profile as a function of the fire angle is shown in Figure 3.

$$B_{eq} = -\frac{X_L - \frac{X_C}{\pi}(2(\pi - \alpha) + \sin(2\alpha))}{X_C X_L} \tag{9}$$

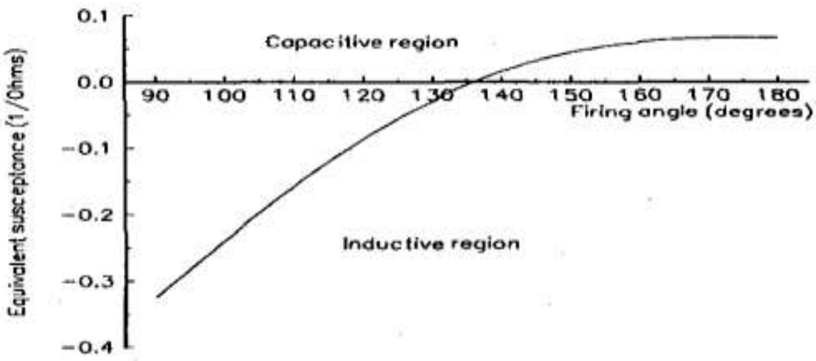

Figure 3. SVC equivalent susceptance as a function of the fire angle

2.3. TCSC Modelling

The original design of controlled series of capacitor along with thyristor, which was proposed as the method of "rapid adjustment of network impedance" by "Vitanatil" et al in 1986 has been shown in Figure 4. In the implementation of the TCSC, several compensators of this type can be connected in series to achieve a nominal voltage and good performance characteristics. This configuration is structurally similar to TSSC, and if the X_L reactor impedance is enough smaller than X_c capacitor impedance, it can function as off and on like TSSC. However, the main idea behind the TCSC design is creating a capacitor with monotonous changes by eliminating part of the effective capacity of capacitor by the TCR. Since TCR in the main frequency of system is reactive impedance with monotonous changes which is controlled by delay angle, the impedance of permanent mode of TCSC is the impedance of a parallel LC circuit that includes X_C fixed capacitor impedance and X_C variable inductive impedance. This means that:

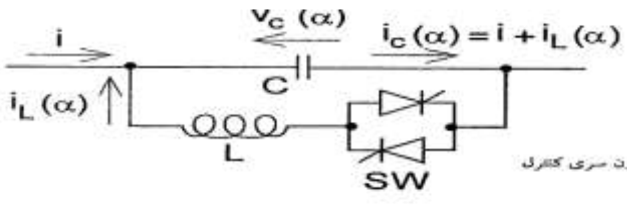

Figure 4. The initial design of Controlled Series Capacitor with thyristor

$$X_{TCSC}(\alpha) = \frac{X_C X_L(\alpha)}{X_L(\alpha) - X_C} \tag{10}$$

In Equation 11 we have:

$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin\alpha}, \quad X_L \leq X_L(\alpha) \leq \infty \tag{11}$$

where $X_L = \omega L$ and α is a delay angle which has been measured from the peak point voltage of capacitor (or its equivalent, zero point of line voltage). Therefore, TCSC demonstrates an LC parallel circuit which is adjustable to the current which is essentially a constant source of alternating current. By changing the impedance of the controlled reactor $X_L(\alpha)$ from the maximum value (infinite) to its minimum value ωL, TCSC increases its minimum capacitor impedance, $X_{TCSC,min} = X_C = 1/\omega L$ (in consequence increases the degree of compensation and series capacitor) accordingly the parallel intensification mode ($X_C = X_L(\alpha)$) is created which is $X_{TCSC,min}$ theoretically infinite. Further fall $X_L(\alpha)$ causes the impedance of TCSC to become inductive and to get to its minimum value where in fact the capacitor is bypassed by TCR. Thus, by conventional arrangement of TCSC in which the impedance of the TCR reactor is smaller than the capacitor impedance, TCSC has two operating range around the enhancement point of its internal circuit:

a. $\alpha_{c\,Lim} \leq \alpha \leq \pi/2$ where $X_{TCSC}(\alpha)$ is the capacitor.
b. $0 \leq \alpha \leq \alpha_{c\,Lim}$ where $X_{TCSC}(\alpha)$ is inductive.

The mentioned range is shown in Figure 5 and Figure 6. TCSC steady state model that was described above is based on TCR in an SVC environment where TCR is supplied by a voltage source. This model is useful for obtaining a general understanding of the actual behavior of the TCSC. However, in the design of TCSC, TCR is closed in parallel with a capacitor rather than a constant voltage source. Dynamic balance between the capacitor and inductor drives out operating voltage form the original condition of sine wave which is connected to a constant flow of line.

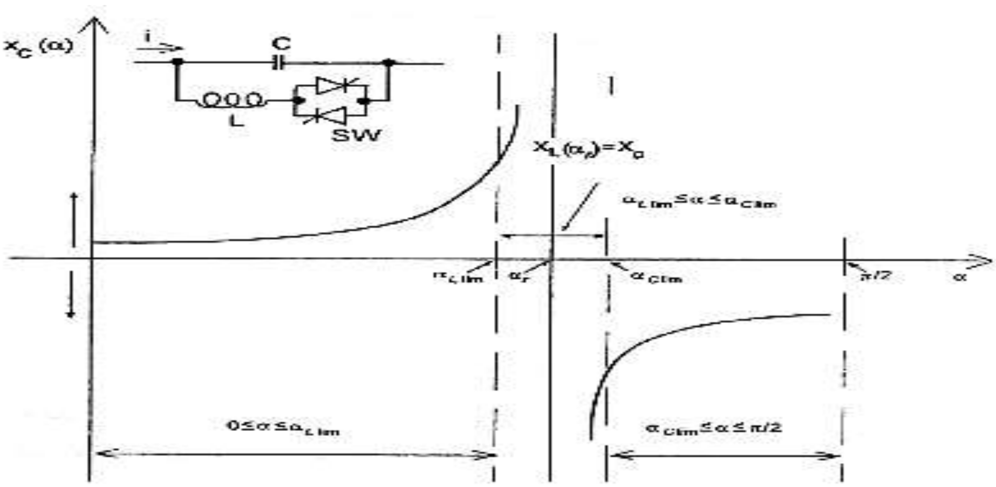

Figure 5. Characteristic of impedance against the delay angle in TCSC

Deeper analysis of the interaction is necessary to understand the actual physical performance and dynamic behavior of TCSC, especially in terms of its impedance in frequencies under synchronizer.

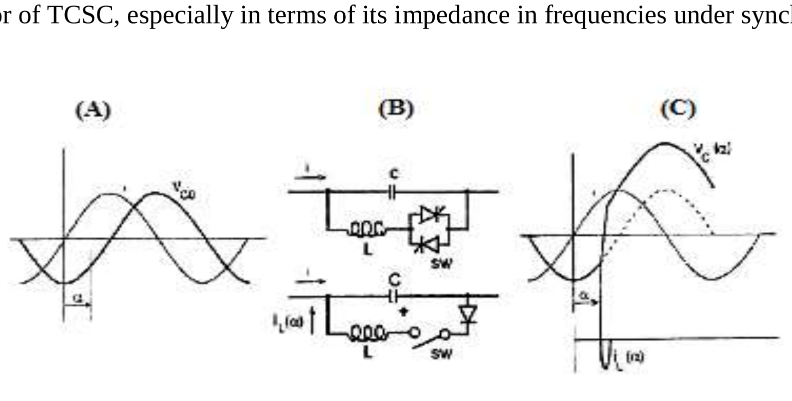

Figure 6. Shows voltage reverse by TCR; (A) the line current and relevant capacitor voltage, (B) the TCSC equivalent circuit at the time of the fire, (C) the resulting capacitor voltage and relevant TCR current.

IEEE defines TCSC as compensation capacitive reactance which includes a series of capacitor banks in parallel with thyristor and inductor in series to produce a series of variable capacitive reactance in transmission lines. So modified two part equations and the injection powers for TCSC.

$$P_{ij}^{c} = V_i^2 G'_{ij} - V_i V_j \left(G'_{ij} \cos \delta_{ij} + B'_{ij} \sin \delta_{ij} \right) \quad (12)$$

$$Q_{ij}^{c} = -V_i^2 \left(B'_{ij} + B_{sh} \right) - V_i V_j \left(G'_{ij} \sin \delta_{ij} + B'_{ij} \cos \delta_{ij} \right) \quad (13)$$

$$P_{ji}^{c} = V_j^2 G'_{ij} - V_i V_j \left(G'_{ij} \cos \delta_{ij} + B'_{ij} \sin \delta_{ij} \right) \quad (14)$$

$$Q_{ji}^{c} = -V_i^2 \left(B'_{ij} + B_{sh} \right) - V_i V_j \left(G'_{ij} \sin \delta_{ij} + B'_{ij} \cos \delta_{ij} \right) \quad (15)$$

Therefore, the injection powers can be expressed as follows:

$$P_i^c = V_i^2 \Delta G_{ij} - V_i V_j \left(\Delta G_{ij} \cos \delta_{ij} + \Delta B_{ij} \sin \delta_{ij} \right) \quad (16)$$

$$P_j^c = V_j^2 \Delta G_{ij} - V_i V_j \left(\Delta G_{ij} \cos \delta_{ij} - \Delta B_{ij} \sin \delta_{ij} \right) \quad (17)$$

$$Q_i^c = -V_i^2 \Delta B_{ij} - V_i V_j \left(\Delta G_{ij} \cos \delta_{ij} - \Delta B_{ij} \sin \delta_{ij} \right) \quad (18)$$

$$Q_j^c = -V_j^2 \Delta B_{ij} - V_i V_j \left(\Delta G_{ij} \sin \delta_{ij} + \Delta B_{ij} \cos \delta_{ij} \right) \quad (19)$$

In the above Equations:

$$\Delta G_{ij} = \frac{x_C r_{ij} (x_C - 2x_{ij})}{({r_{ij}}^2 {x_{ij}}^2)({r_{ij}}^2 + (x_{ij} - x_C)^2)} \quad (20)$$

$$\Delta B_{ij} = \frac{-x_C r_{ij} ({r_{ij}}^2 - x_{ij} + x_C r_{ij})}{({r_{ij}}^2 + {x_{ij}}^2)({r_{ij}}^2 + (x_{ij} - x_C)^2)} \quad (21)$$

$$\Delta G'_{ij} = \frac{r_{ij}}{{r_{ij}}^2 + (x_{ij} - x_C)^2} \quad (22)$$

$$\Delta B'_{ij} = \frac{-(x_{ij} - x_C)}{{r_{ij}}^2 + (x_{ij} - x_C)^2} \quad (23)$$

3. ROBUST CONTROLLER DESIGN (H_∞)

Robust controller design is used for the damping of low frequency oscillation modes. For the design of this type of controller, three operating points are considered. The first operating point is related to the time when the heavy load is connected to the generator. The second operating point of system is the common operating point of the system and the third point is when the system is under light load. Figure (6) shows the formula of design problem in a general standard framework. Performance characteristics and uncertainty of multiplicative is specified in input with weights of *Wc* and *Ws*. These weights play a very important role in the controller performance. The weights are determined according to the physical nature of the problem. Finally, the exact amount of these weights is determined by trial and error [15, 19]. The final amount of weights due to nonlinear system has been selected by frequent simulation as follows:

$$w_s = 100 \frac{s+1}{s+400} \quad (24)$$

$$w_c = \frac{s+2}{s+3000.2} \quad (25)$$

When the main uncertainty is the impedance change between infinite bass and the generator, *jXe* impedance represents impedance parallel between the infinite bass and the generator bass. Normally, when all

transmission lines between infinite bass and generator are in service, *Xe* is relatively low and such a network is called stiff.

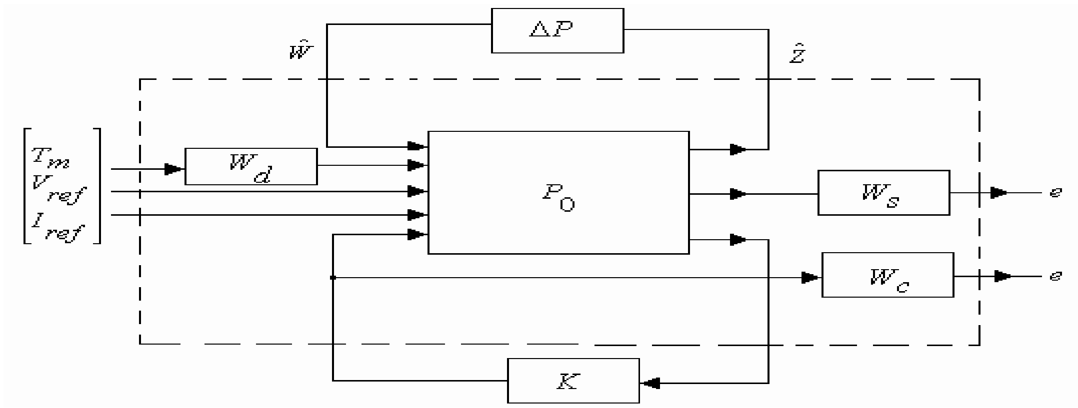

Figure 7. The standard form of robust control problem

When a number of transmission lines are out of service, like when an error occurs, *Xe* may be relatively large and such a network is called weak. For such a system (like single infinite machine in Figure 8, *Xe* changes are considered from 0.6 to 1.2 per unit [16, 17, 18].

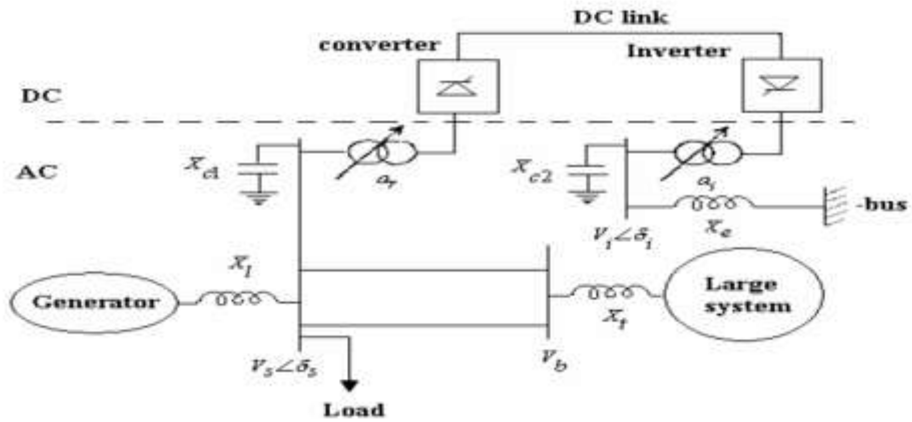

Figure 8. Power system of AC-DC

Table 1. Critical operating points of system

System	Xe	Pg (p.u)	Qg (p.u)	f (Hz)	ξ(%)
Stiff	0/6	١	0/008	1/64	5/3
Median	0/9	١	0/015	1/23	2/4
Eak	1/2	١	0/03	1/01	- 1/01

Due to parameter changes of the system according to the table (1) matrix parameters of space state are transformed that in consequence these changes lead to uncertainty in the mentioned matrix coefficients.

4. SIMULATION

After determining the generalized system for the studied power system, MATLAB2013a software was used to implement the design process and simulation. The studied system for testing is the equivalent model system of the United Kingdom to New York with 16 generators, 68 bass and 5 areas. Furthermore, an

HVDC transmission system is configured between bass 1 (area 4) and bass 2 (area 5). A shunt FACTS device (SVC) was installed at bass 51 (in area 4) and a (TCSC) series FACTS device was installed between the bass 46 (area 4) and bass 49 (in area 3). Generators of G1 to G9 are located in the UK (area 5) while the generators of G10 to G13 are located in New York (area 4). Generators of G14 (area 1), G15 (area 2) and G16 (area 3) are equivalent generators in the neighborhood of New York.

4.1. The first phase: The Dynamic Response of the Equivalent of the Generator in All Areas Before Positioning HVDC and FACTS

In this case, the dynamic response of the equivalent generator before positioning HVDC and FACTS has been examined in all areas. Figure 8 that is related to the G1 to G9 generators (area 5) shows changes over time. According to the Figure 9, system in this case shows high amplitude oscillations and inappropriate performance.

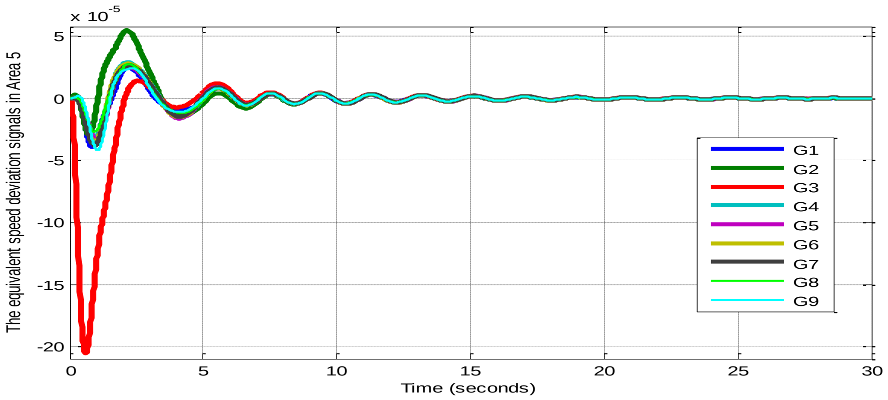

Figure 9. The equivalent of the signal of the system speed deviation in area 5

4.2. The second phase: Dynamic response of the equivalent of the generator in all areas after locating HVDC

In this case, the dynamic response of the equivalent of the generator in all areas after locating HVDC between the bass 1 (in area 4) and bass 2 (in area) has been examined. Figure 10 that concerns the generators of G1 to G16 (areas 1 to 5) shows changes Δω over time for all areas. As shown in the Figure 10 oscillations of most of the generators in this case in comparison to the first case have less amplitude.

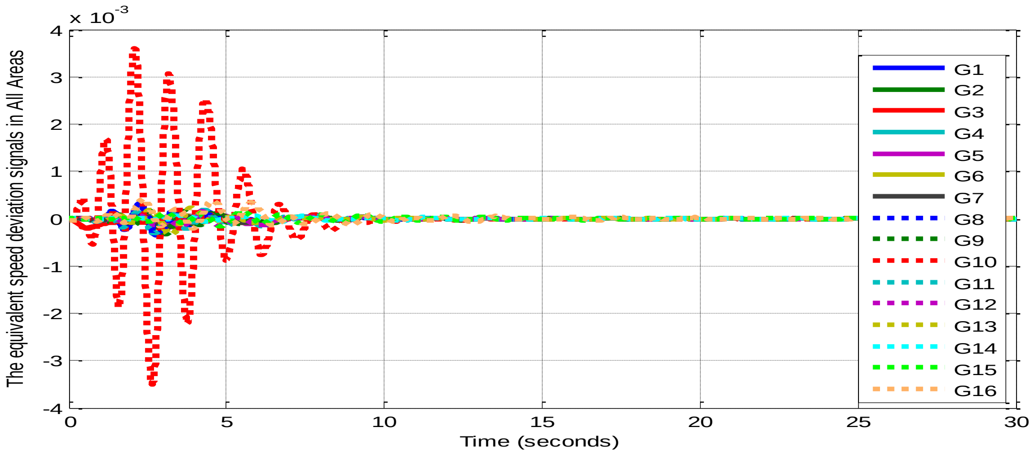

Figure 10. The equivalent signal of speed deviation of five areas system with the presence of HVDC

4.3. The third phase: dynamic response of equivalent of generator in all areas after locating FACTS

In this case, the dynamic response of equivalent of generator in the circuit in all areas after installing a (SVC) shunt FACTS at bass 51 (in area 4) and a FACTS series device of (TCSC) between the bass 46 (in area 4) and bass 49 (in the area 3) has been checked. Figure 11 that is related to the generators of G1 to G16 (areas 1 to 5) shows changes $\Delta\boldsymbol{\omega}$ over time for all areas.

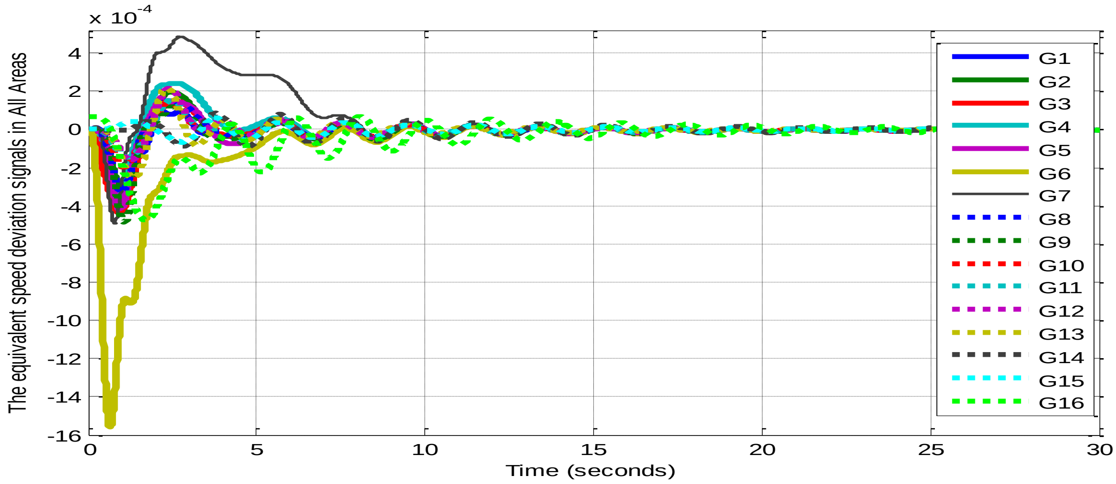

Figure 11. The equivalent signal of speed deviation of five areas system with the presence of FACTS

As it is shown in the Figure 11 oscillations in the presence of FACTS equipment compared with the first case are removed faster and has less amplitude.

4.4. The fourth phase: The dynamic response of the equivalent of generator in all areas after locating HVDC and FACTS

In this case, the dynamic response of the equivalent of generator in all areas after locating HVDC between the bass 1 (in area 4) and bass 2, an (SVC) shunt FACTS device was installed at bass 51 (in area 4) and a (TCSC) FACTS Series device between the bass 46 (in area 4) and bass 49 (in area 3) have been checked in the circuit. Figure 12 that concerns the generators G1 to G9 (area 5) shows changes over time. This Figure represents that resistant controller had better performance when HVDC and FACTS are present in the circuit in comparison to their nonexistence in the circuit. The low frequency oscillations in different operating points have also been clarified.

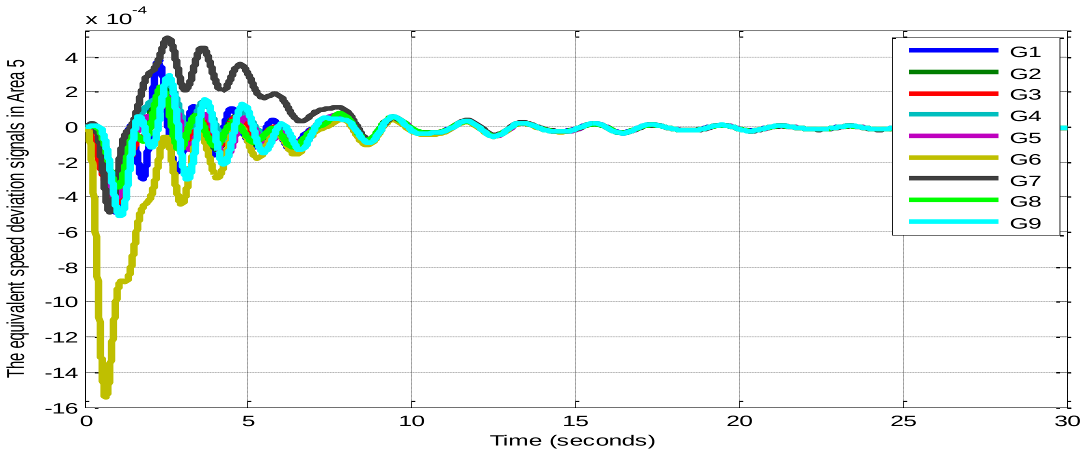

Figure 12. The equivalent signal of speed deviation of system in area 5

5. CONCLUSION

This paper presents a new fixative design method for coordinated connection of HVDC and FACTS by using resistant control method (H_∞). Simulation results show that the controller is more effective than traditional methods for the system stability that is it ensures the system stability for all allowable uncertainties and only requires boundary parameters changes in the process of designing. In addition, in this study a coordinated powerful approach for HVDC and FACTS by controlling a wide area for stabilizing oscillations among different areas was investigated. This method can significantly increase the efficiency of the system by the FACTS and HVDC equipment.

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